no action

OH

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: August 21, 1975

Project Title: Development of a Mechanized Transformer Test Procedure

Project No: E-21-666

Principal Investigator Dr. C. O. Alford

Sponsor: General Electic Company; Rome , Georgia

Agreement Period: From 8/20/75 Until 1/19/76

Type Agreement: Standard Industrial Research Agreement

Amount: $8,439

Reports Required: Monthly Progress

Sponsor Contact Person (s):

Mr. R. A. Nelson, Manager
Advance Development Engineering
Building No. 2, Laboratory
Medium Transformer Department
General Electric Company
Redmond Circle
Rome, Georgia 30161

Assigned to: Electrical Engineering

COPIES TO:

Principal Investigator
School Director
Dean of the College
Director, Research Administration
Director, Financial Affairs (2)
Security-Reports-Property Office
Patent Coordinator

Library
Rich Electronic Computer Center
Photographic Laboratory
Project File
Other

RA-3 (6-71)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

no action
no action
[illegible]

Date: April 28, 1977 [illegible]

$436 [illegible]

Project Title: Development of a Mechanized Transformer Test Procedure

Project No: E-21-666

Project Director: Dr. C. O. Alford

Sponsor: General Electric Company; Rome, GA 30161

Effective Termination Date: 1/19/76

Clearance of Accounting Charges: 1/19/76

Grant/Contract Closeout Actions Remaining: None

- _ Final Invoice and Closing Documents
- _ Final Fiscal Report
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ____________

Assigned to: Electrical Engineering (School/Laboratory)

COPIES TO:

Project Director
Division Chief (EES)
School/Laboratory Director
Dean/Director—EES
Accounting Office
Procurement Office
Security Coordinator (OCA) ✓
Reports Coordinator (OCA)

Library, Technical Reports Section
Office of Computing Services
Director, Physical Plant
EES Information Office
Project File (OCA)
Project Code (GTRI)
Other ____________

CA-4 (3/76)

E-21-666

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
ELECTRICAL ENGINEERING

October 8, 1975

Mr. R. A. Nelson, Manager
Advance Development Engineering
Building No. 2, Laboratory
General Electric Company
Redmond Circle
Rome, GA 30161

RE: Progress Report No. 1: Project E-21-666, Development of a Mechanical Transformer Test Procedure

Dear Mr. Nelson:

The research team has been organized and assignments made for the initial phase of the research. Members of the team and their respective assignments are:

Dr. C. O. Alford - Project Director
Mr. J. R. Cordova - Investigation of sampling and A/D hardware.
Mr. R. C. Gibson - Fortran programming and simulation of the sampling and computation procedure.
Mr. W. R. Casto - Analysis of errors as a function of sampling rate, numerical method and other critical parameters.

The latter three team members are new graduate students pursuing a Master of Science degree. This quarter they are each assigned 1/3 time to this project as a research assistant.

After the team members have had an opportunity to properly digest the problem, formulate an approach and obtain some initial results we will make a presentation to General Electric personnel. Tentatively this is being planned for October 16, 1975. This date will be confirmed by phone later this week.

Sincerely,

Cecil O. Alford
Associate Professor of
Electrical Engineering

km

E-21-666

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

SCHOOL OF
ELECTRICAL ENGINEERING

November 7, 1975

Mr. R. A. Nelson, Manager
Advanced Development Engineering
Building No. 2, Laboratory
General Electric Co.
Redmond Circle
Rome, GA 30161

Re: Progress Report No. 2: Project E-21-666, Development of a Mechanized Transformer Test Procedure

Dear Mr. Nelson:

The research team visited General Electric October 21, 1975. Discussions were held with Misters John Crouse, Wilkes Burnett, Charles Boyles and Gus Lind. Mr. Burnett followed these discussions by showing the Ga. Tech students the manufacturing and test facilities. From their perspective this is a valuable and educational experience which is helping to develop them into a real engineer.

Thus far our work has concentrated on computational aspects of finding V_{RMS}, V_{AVG} and P_{AVG} by numerical methods. We have used the computer to study the effects of; (1) sampling rate, (2) numerical method, and (3) the number of cycles over which the integral is to be taken. Our early studies concentrated on a single sine wave. Since the visit we have made some studies with a fundamental and third harmonic. Table 1 shows some typical results which have been obtained thus far. Errors are given in percent. The third harmonic is in phase with the fundamental and has an amplitude of 30% of the fundamental amplitude.

Our next studies will be directed toward:

1. The effect of using 16 bit arithmetic instead of the 60 bit currently being used.

2. The effect of using 16 bit data which is all we can expect on the test facility.

3. The determination of the maximum phase shift to be introduced by the samplers and the effect of this phase shift on the computations.

We will call to make arrangements for another visit in the near future.

Sincerely,

C. O. Alford
Associate Professor of
Electrical Engineering

		ERROR IN PERCENT	
Sample Rate	No. of Cycles	V_{RMS}(FUND)	V_{RMS}(FUND + THIRD)
253	1	.00762	.0125
253	5	.00762	.0125
493	1	.00202	.0033
493	5	.00202	.0033

		ERROR IN PERCENT	
Sample Rate	No. of Cycles	V_{AVG}(FUND)	V_{AVG}(FUND + THIRD)
253	1	.00514	.0089
253	5	.00514	.0089
493	1	.00135	.0023
493	5	.00135	.0023

FOR POWER FACTOR ANGLE = 88°		ERROR IN PERCENT	
Sample Rate	No. of Cycles	P_{AVG}(FUND)	P_{AVG}(FUND + THIRD)
253	1	2.17×10^{-9}	4.88×10^{-9}
253	5	2.37×10^{-9}	5.29×10^{-9}
493	1	1.39×10^{-9}	2.91×10^{-9}
493	5	1.29×10^{-9}	2.96×10^{-9}

Table 1. Error Analysis Summary

E-21-666

Ser
Cys

REPORT TO THE

GENERAL ELECTRIC COMPANY

ON

DEVELOPMENT OF A MECHANIZED
TRANSFORMER TEST PROCEDURE

December 1975

BY THE

ELECTRIC POWER LABORATORY

OF THE

SCHOOL OF ELECTRICAL ENGINEERING

AT

GEORGIA INSTITUTE OF TECHNOLOGY

PARTICIPANTS:

GRADUATE STUDENTS

Ron Casto
Jim Cordova
Bob Gibson
Bill Poston

FACULTY

Dr. Cecil Alford,
Program Manager

INTRODUCTION

This report discusses a technique for obtaining the digitized three-phase voltages and currents necessary to specify transformer characteristics.

Accuracy of results obtained by this technique is discussed for variations in sampling rate, phase angle, the number of waveform cycles considered, and the numerical method. In addition, error reducing techniques are presented, and special considerations such as third harmonic analysis and input data limiting are considered.

Hardware specifications are given in terms of speed, accuracy, and cost. Overall system considerations are also presented.

APPROACH

The analysis that follows shows the basic computational algorithms and techniques necessary to calculate single-phase power from input samples of voltage and current. Once these quantities and their accuracies are determined for each phase involved, a simple numerical manipulation yields the corresponding three-phase parameters desired. An example of this manipulation is given in the discussion following.

I. BASIC CALCULATIONS

The program computes percentage errors for V_{RMS}, V_{AVG}, and P_{AVG} by comparing "true" values with those values calculated from the input samples, where:

$$\% \text{ Error} = \frac{\text{"True" Value - Calculated Value}}{\text{"True" Value}} \times 100\%$$

and "true" values are:

$$V_{RMST} = A/\sqrt{2} \qquad I_{RMST} = A/\sqrt{2}$$

$$V_{AVGT} = 2A/\pi \qquad V_{AVGT} = 2A/\pi$$

$$P_{AVGT} = V_{RMST} \cdot I_{RMST} \cdot \cos(\text{PHASE})$$

The calculated values depend upon the following parameters (see Figure 1):

A. Sampling Rate, 'K1':

For simulation purposes K1 was varied from 13 to 533 samples/cycle in steps of 40 samples/cycle.

B. Phase Angle, 'PHASE':

Phase variations of 88° to 92° in increments of 0.5° were used.

C. Number of waveform cycles, 'K2':

These integration cycles were chosen as 1 to 17 cycles in 4-cycle increments.

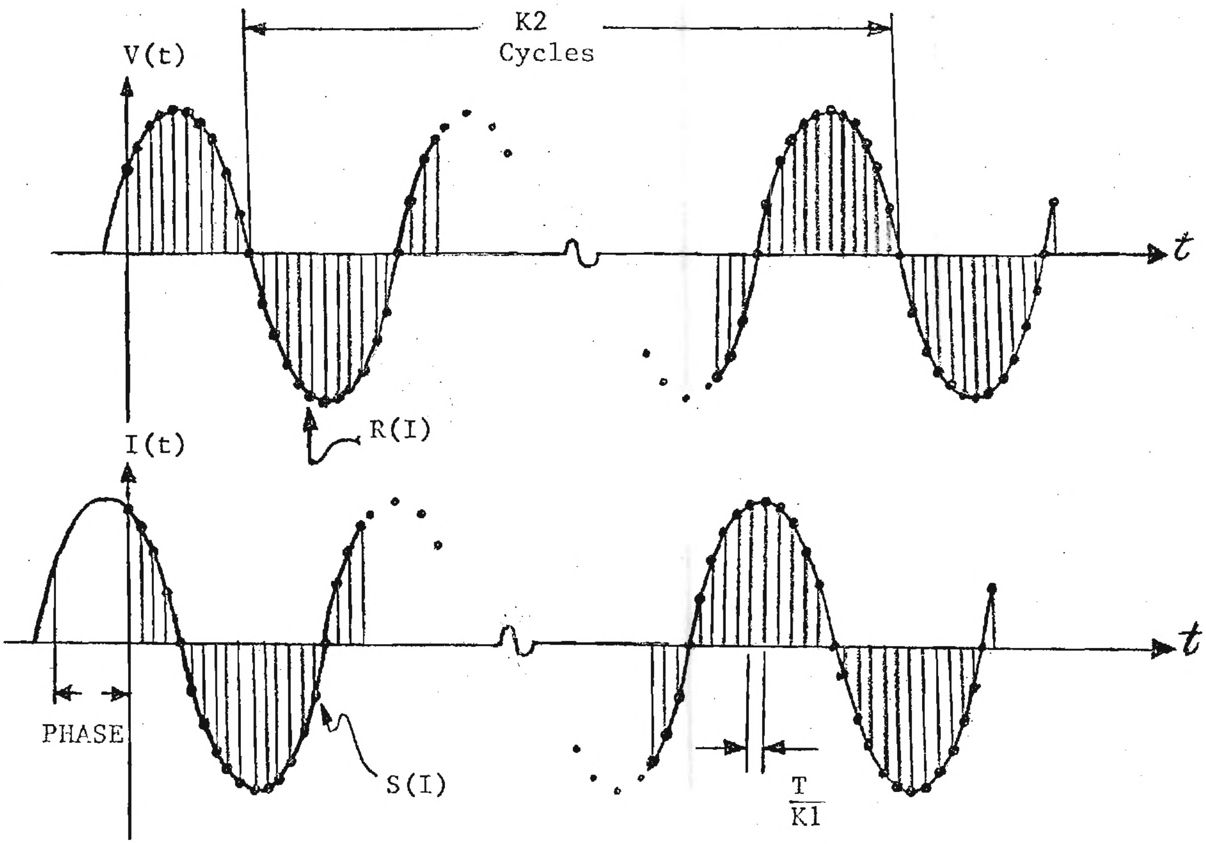

Fig. 1...voltage and current sampled at K1 samples/cycle over K2 cycles.

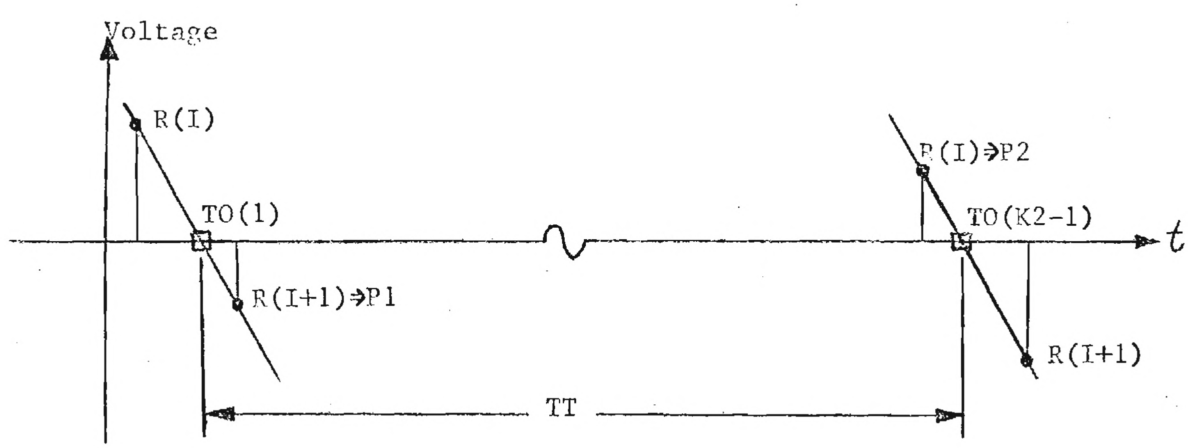

Fig.2...Detail of crossover points.

D. Numerical Methods:

The methods used require knowledge of sample values, sample times, zero-crossing points, and the total integration time. The techniques used in the program follow.

To simulate input data, ordered arrays of voltage and current were generated from the following equations:

$$V = R(I) = A \sin (THETA \cdot TI(I))$$

$$I = S(I) = A \sin (THETA \cdot TI(I) + PHASE)$$

where,

(I) = sample point (1 to 10,000)

TI(I) = time that sample (I) was taken

THETA = 2π (frequency of the waveform) = $2\pi(IF) = 2\pi/T$

A third array used to compute percentage error of power on a point-by-point basis is formed by letting (see P_{AVGF} function):

$$P(I) = R(I) \cdot S(I).$$

Power error is also calculated using

$$P_{AVGRM} = V_{RMS} \cdot I_{RMS} \cdot COS\ (PHASE),$$

where V_{RMS} and I_{RMS} are calculated from the RMS function.

II. SUBROUTINE AND FUNCTION

A. Subroutine 'CP':

CP is used to determine the time of the N zero-crossover points TO(N), the end-points of the integration period (P1 and P2, respectively), and the period of integration TT. (See Figure 2.)

The crossover points for voltage and current are found separately, while the power zero points are those of the voltage array. Each crossover point is obtained using linear interpolation between two successive samples of opposite sign (that is, for those sample points where R1 and R(I+1) are both negative in the equation: $R1 = R(I) \cdot R(I+1)$). Half-cycle zero points are ignored.

Therefore,

$$TO(N) = \frac{R(I)}{R(I) - R(I+1)} \cdot [TI(I+1) - TI(I)] + TI(I) \text{ ; for } N = 1 \text{ to } (K2-1).$$

Thus, P1 and P2 are the first nonzero samples within TO(0) and TO(K2-1), respectively, and

$$TT = TO(K2-1) - TO(1).$$

B. Function 'AVG':

Average values of voltage and current are formed by averaging sequential pairs of samples taken from the voltage or current arrays, summing over the total time interval, and dividing by TT.

The average for any pair of adjacent samples is:

$$AVG = \left| \frac{X(I) + X(I+1)}{2} \right| \cdot TI(I) \text{ ; for } X(I) = R(I) \text{ or } S(I),$$

and the total over K2 cycles is:

$$AVG = \sum_{P1}^{P2} \frac{AVG}{TT}$$

In addition, an error reducing technique is used for samples located about a zero-crossing. The average value for these samples is taken as the average of two similar triangles formed by the samples, the sample times, and the distance to the zero.

The base of a triangle to the left of a zero is:

$$B = \frac{|X(I)|}{|X(I)| + |X(I+1)|} \cdot TI(1),$$

where TI(1) is equivalent to the time between samples. (Therefore, the base of a triangle to the right of a zero is: TI(1) - B.)

Thus, the average of two samples about a zero-crossing is:

$$AVG = \frac{|X(I)| \cdot B}{2} + \frac{|X(I+1)| \cdot [TI(1)-B]}{2} .$$

C. Function 'P_{AVGF}':

The point-to-point power average is calculated using equations exactly as those of 'AVG' except no absolute values are used (of course, X(I) = P(I).)

D. Function 'RMS':

RMS values are found by summing mean-square values of sequential pairs of samples taken from the voltage and current arrays, dividing by TT, and finding the square-root.

Thus, the mean-square value of two samples is:

$$SQ = \left[\frac{X(I) + X(I+1)}{2} \right]^2 \cdot TI(1) ,$$

hence,

$$RMS = \left(\sum_{P1}^{P2} \frac{SQ}{TT} \right)^{\frac{1}{2}}$$

Where, as in the AVG function, mean-square values at crossover points are:

$$SQ = \frac{X^2(I) \cdot B}{2} + \frac{X^2(I+1) \cdot [TI(1)-B]}{2} .$$

Note: An alternate approach for non-crossover samples, using

$$SQ = \frac{X(I)^2 + X(I+1)^2}{2} \cdot TI(1) ,$$

would yield lower error results but was not investigated since the present method resulted in error rates well within specified limits.

III. ERRORS

Error specifications were:

Error (P_{AVG}) $\leq$ 1%

Error (RMS) $\leq$ .1%

Error (AVG) $\leq$ .1%.

Error dependence upon sampling rate and phase angle is shown in Figures 3a and 3b for no bit-limiting on the input (no limiting guarantees 15 digit input accuracy).

Inspection of Figure 3a reveals errors less than 0.2% for a sampling rate of approximately 60 samples/cycle and an exponential decrease as the sampling rate increases.

Figure 3b shows that error is well within limits for sampling rates of 253 samples/cycle and 533 samples/cycle.

IV. SPECIAL CONSIDERATIONS

Considerations due to the presence of a third harmonic and the effect of data input limiting are given as follows:

A. Third Harmonic:

In this case, only the values of the input samples and the "true" values change. Therefore, for simulation purposes, the input arrays were formed from:

V = R(I) = A sin (THETA·TI(I)) + (0.3) A sin (3·THETA·TI(I))

I = S(I) = A sin (THETA·TI(I) + PHASE) +

(0.3) A sin (3·THETA·TI(I) + PHASE),

where the amplitude of the third harmonic was arbitrarily chosen as three-tenths of the fundamental amplitude.

The RMS and AVG values are calculated as before, and the "true" values are now:

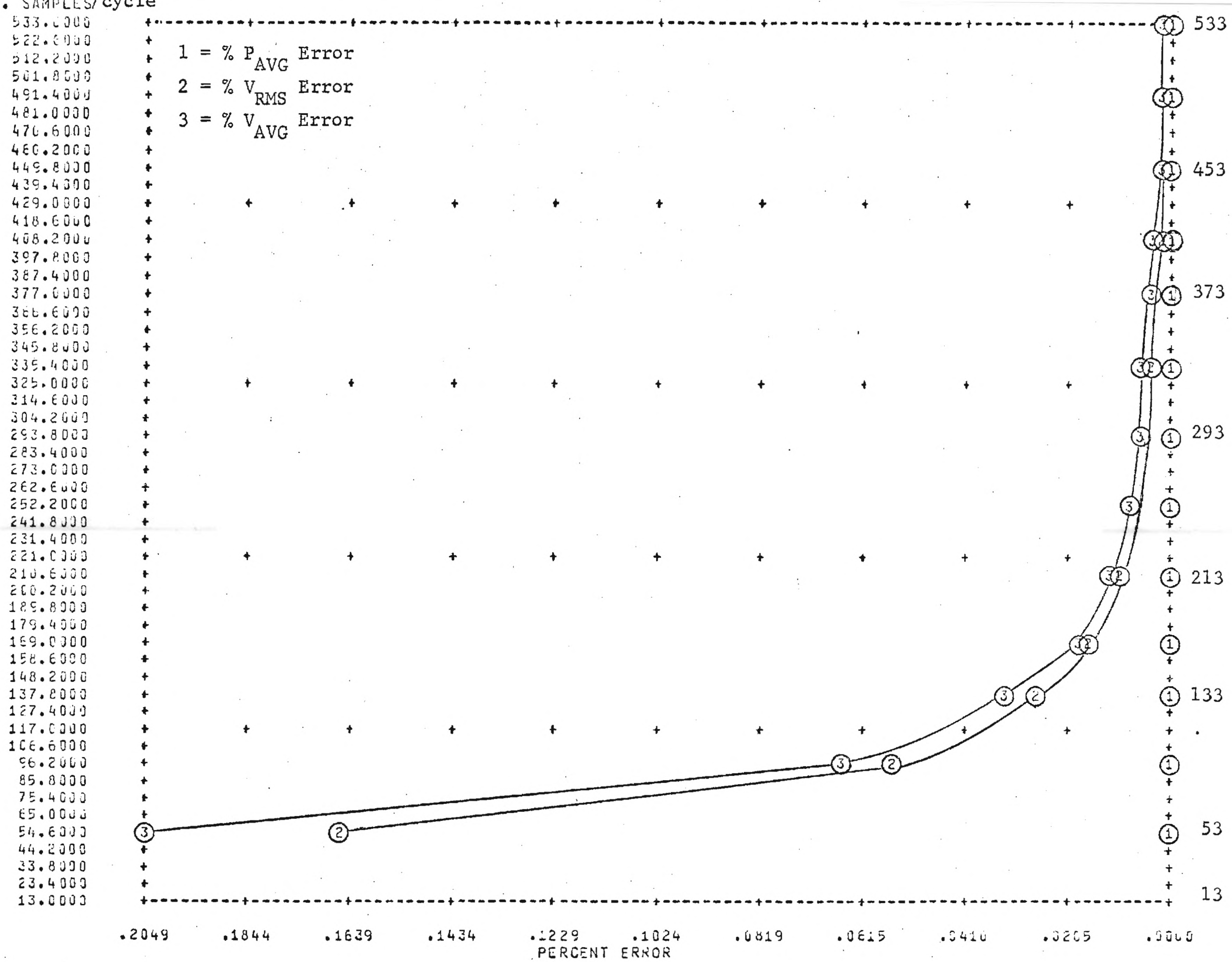

Fig 3a. Error vs. Sample Rate (No limiting, Fundamental only).

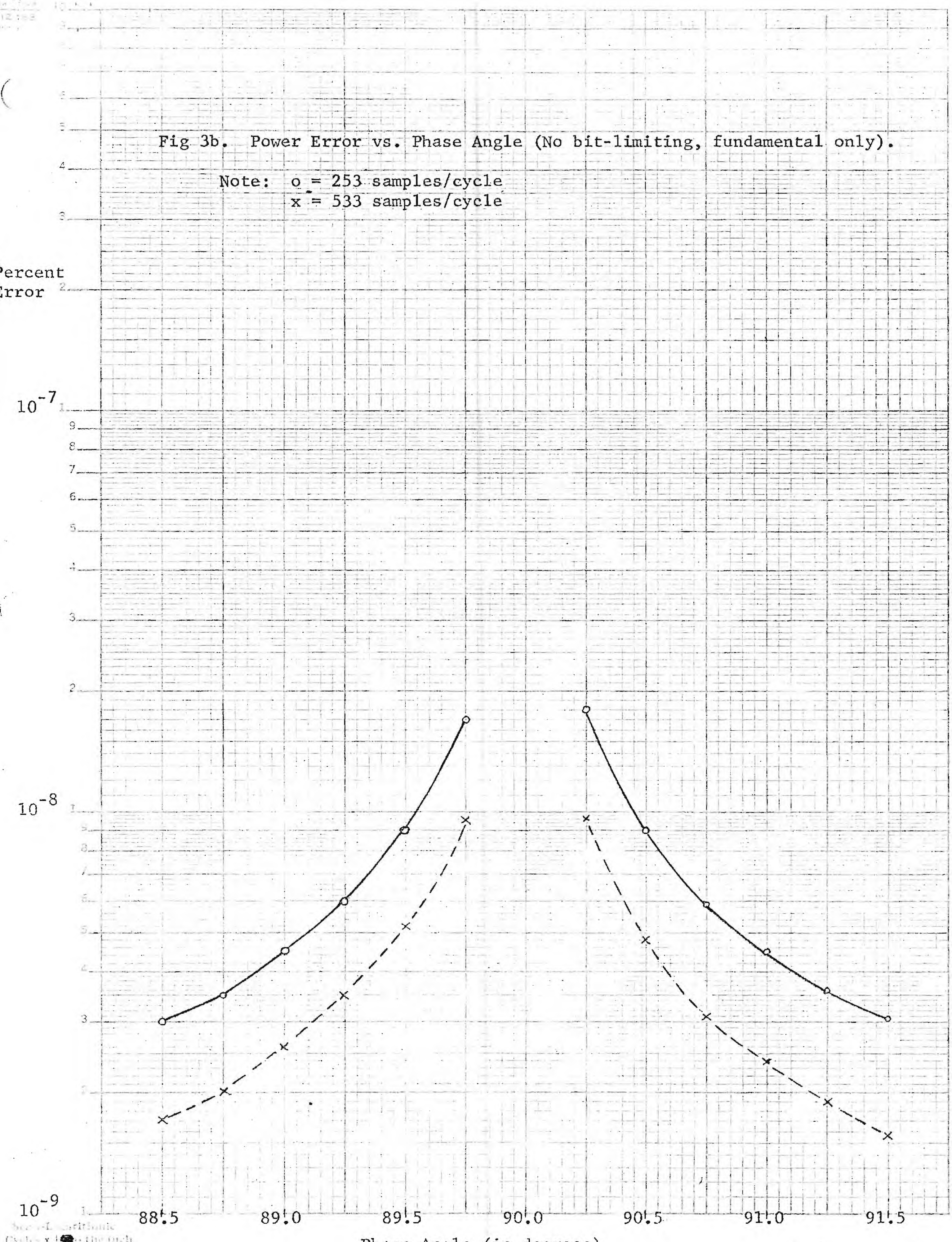
Fig 3b. Power Error vs. Phase Angle (No bit-limiting, fundamental only).
Note: o = 253 samples/cycle
x = 533 samples/cycle
Percent Error
10^{-7}
10^{-8}
10^{-9}
88.5
89.0
89.5
90.0
90.5
91.0
91.5
Phase Angle (in degrees)

$$V_{RMST} = (1.3)\ A/\pi \qquad I_{RMST} = (1.3)\ A/\pi$$

$$V_{AVGT} = (1.3)\ A/\sqrt{2} \qquad I_{AVGT} = (1.3)\ A/\sqrt{2}$$

$$P_{AVGT} = I_{RMS} \cdot V_{RMS} \cdot \cos(\text{PHASE})$$

Error curves including third harmonic considerations are shown in Figures 4a and 4b. As can be seen, specifications are met for sampling rates above approximately 93 samples/cycle.

B. Data Input Limiting:

To observe the effects on errors due to limiting the digit accuracy per sample, four-digit and five-digit inputs were simulated.

Four-digit limiting in the program is accomplished by letting (see Table 1):

$$\text{ILIMIT} = X(I) \cdot 1000 \qquad \text{(i.e., form an integer)}$$

$$X(I) = \text{ILIMIT}/1000\ ,$$

where

$$X(I) = R(I) \text{ and } S(I).$$

Similarly, a five-digit limit is imposed upon X(I) by replacing 1000 with 1000 in the equalities above.

Error curves for four-digit and five-digit accuracy are shown in Figures 5a, b, c and 6 respectively.

Error is acceptable (see Figure 5a) for a sampling rate greater than 93 samples/cycle, and Figure 5b indicates that no improvement is obtained with an increase in the number of cycles sampled. Figure 5c shows that

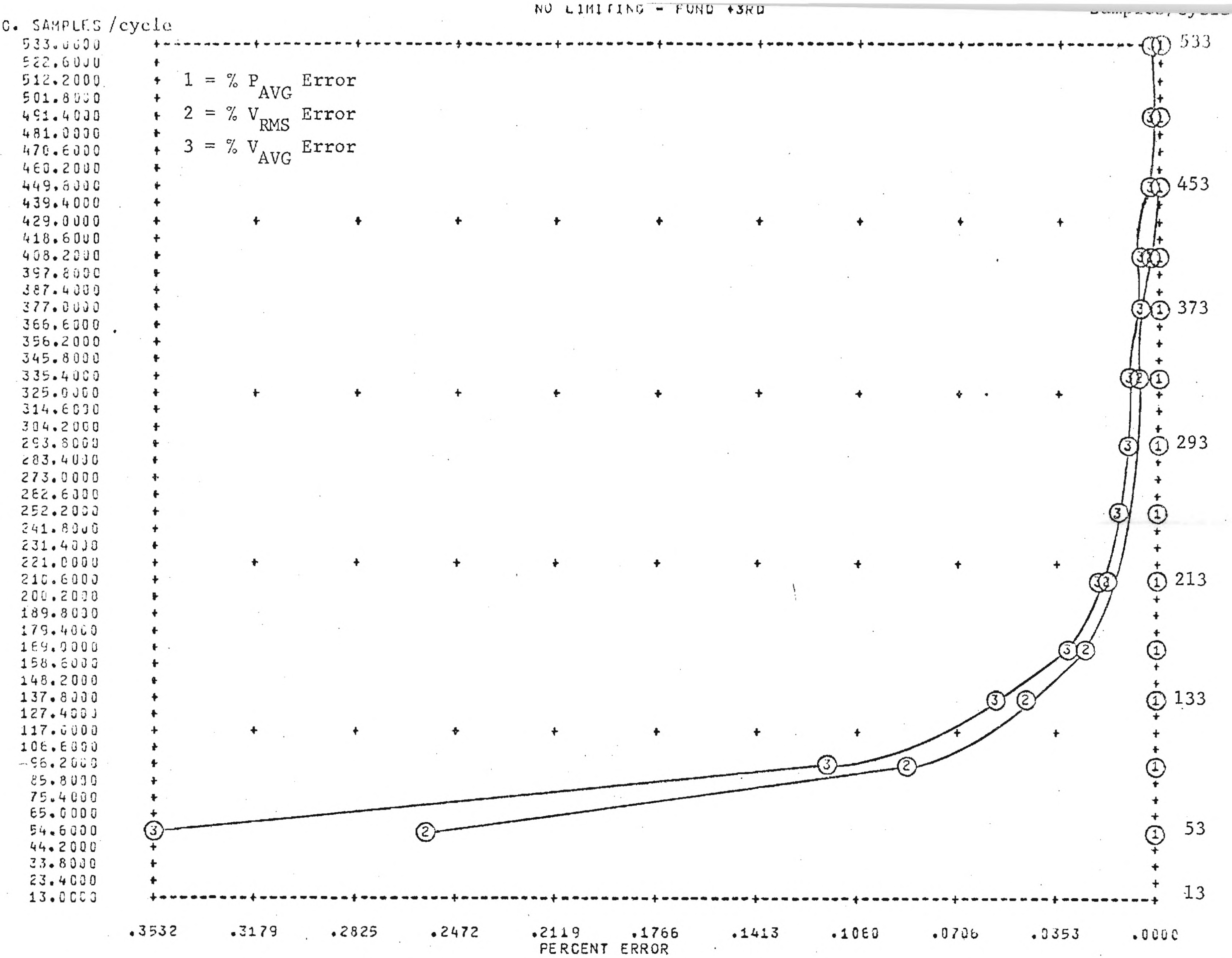

Fig 4a. Error vs. Sample Rate (No limiting, fundamental + 3rd harmonic).

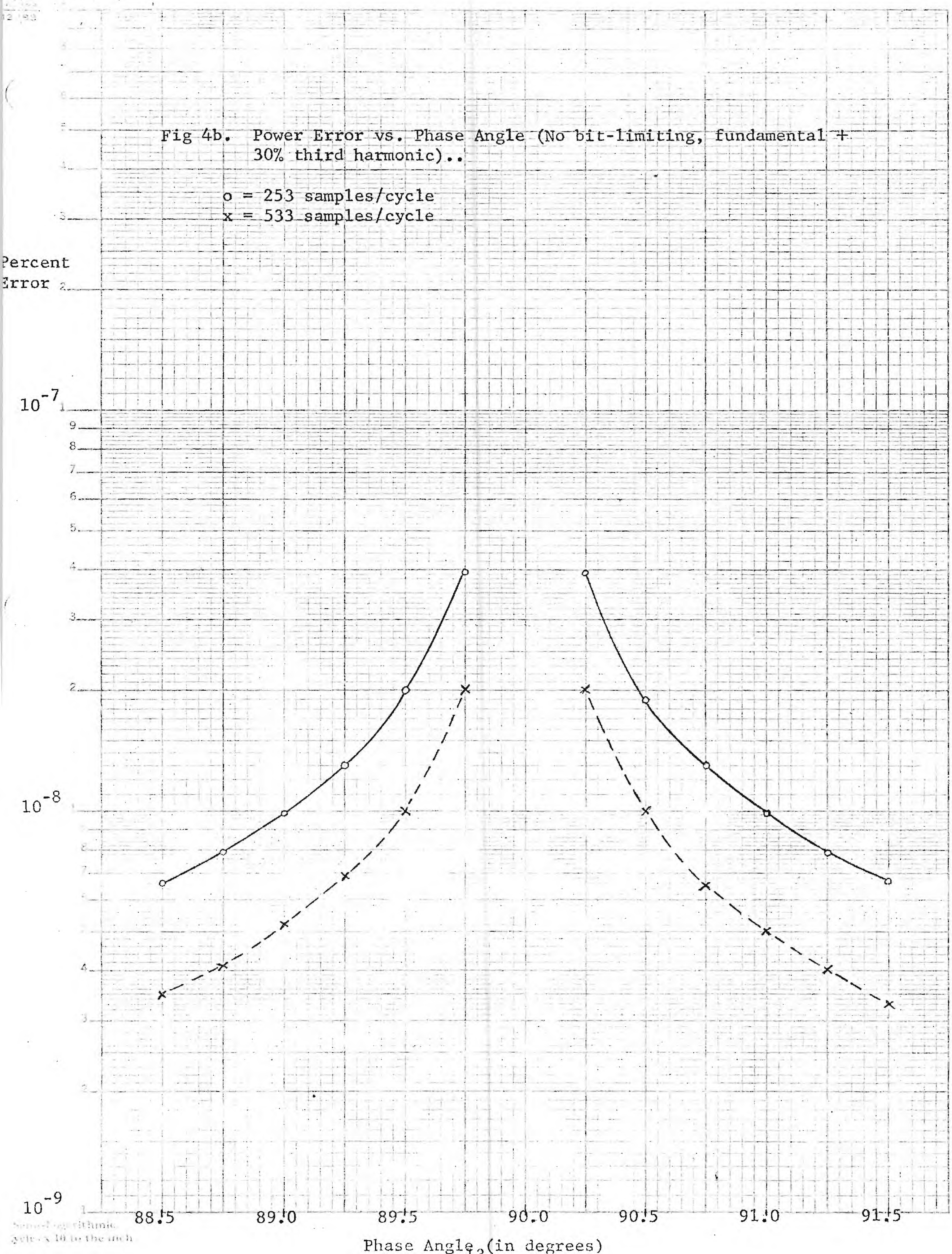
Fig 4b. Power Error vs. Phase Angle (No bit-limiting, fundamental + 30% third harmonic)..
o = 253 samples/cycle
x = 533 samples/cycle
Percent Error
10^{-7}
10^{-8}
10^{-9}
88.5
89.0
89.5
90.0
90.5
91.0
91.5
Phase Angle (in degrees)

EXAMPLE OF BIT-LIMITING DATA TO 4 DECIMAL DIGITS

VOLTAGE ARRAY VALUES			CURRENT ARRAY VALUES		
INITIAL VALUES	ILIMIT INTEGER VALUES	R(I) LIMITED VALUES	INITIAL VALUES	ILIMIT INTEGER VALUES	S(I) LIMITED VALUES
.59137	591	.59100	4.98252	4982	4.98200
1.17443	1174	1.17400	4.89814	4898	4.89800
1.74101	1741	1.74100	4.74500	4745	4.74500
2.28315	2283	2.28300	4.52526	4525	4.52500
2.79323	2793	2.79300	4.24198	4241	4.24100
3.26411	3264	3.26400	3.89916	3899	3.89900
3.68917	3689	3.68900	3.50161	3501	3.50100
4.06243	4062	4.06200	3.05490	3054	3.05400
4.37867	4378	4.37800	2.56530	2565	2.56500
4.63345	4633	4.63300	2.03970	2039	2.03900
4.82318	4823	4.82300	1.48546	1485	1.48500
4.94520	4945	4.94500	.91037	910	.91000
4.99780	4997	4.99700	.32250	322	.32200
4.98025	4980	4.98000	-.26990	-269	-.26900
4.89278	4892	4.89200	-.85851	-858	-.85800
4.73663	4736	4.73600	-1.43507	-1435	-1.43500
4.51399	4513	4.51300	-1.99148	-1991	-1.99100
4.22798	4227	4.22700	-2.51994	-2519	-2.51900
3.88262	3882	3.88200	-3.01302	-3013	-3.01300

TABLE 1.

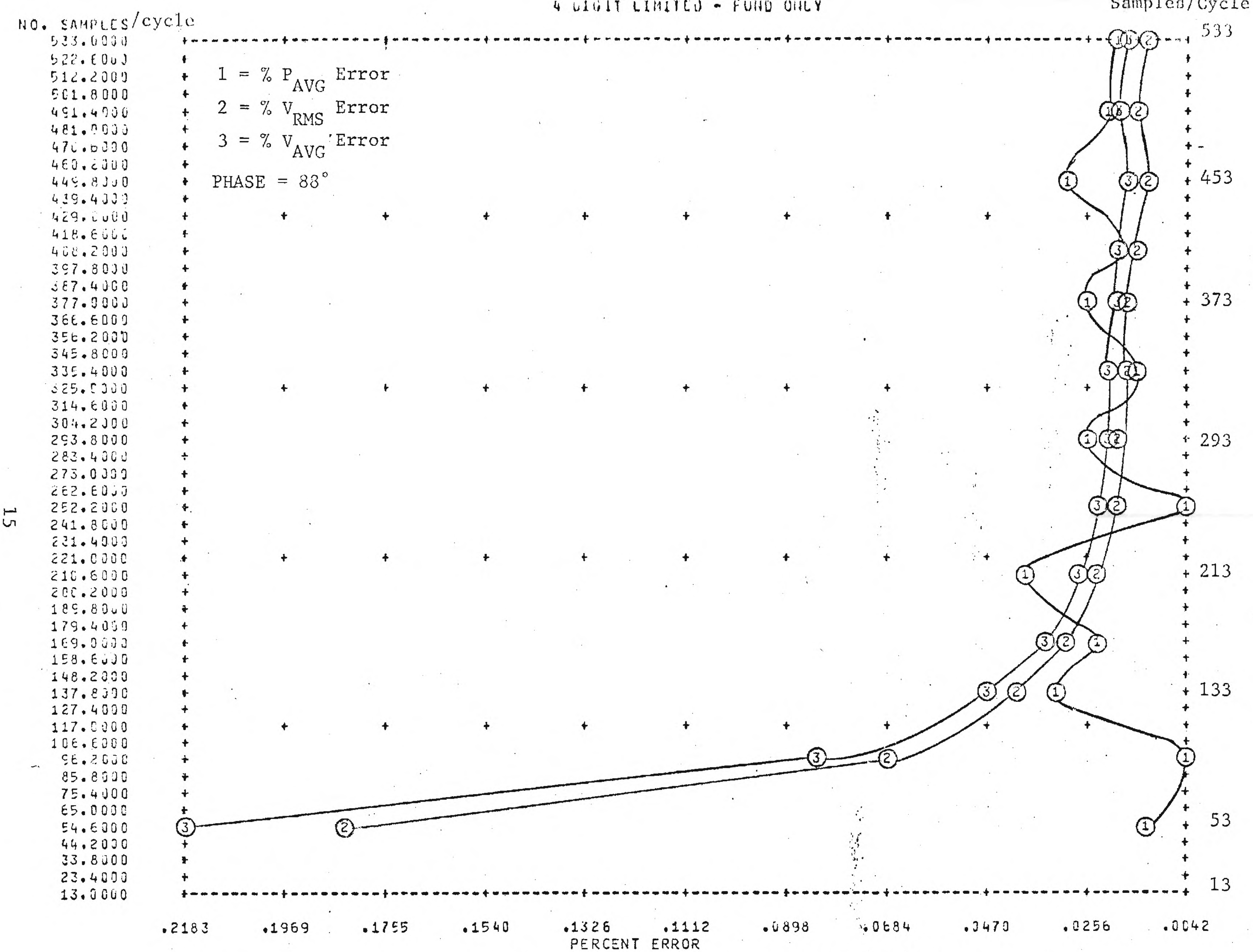

Fig 5a. Error vs. Sample Rate (4-digit bit-limited, fundamental only).

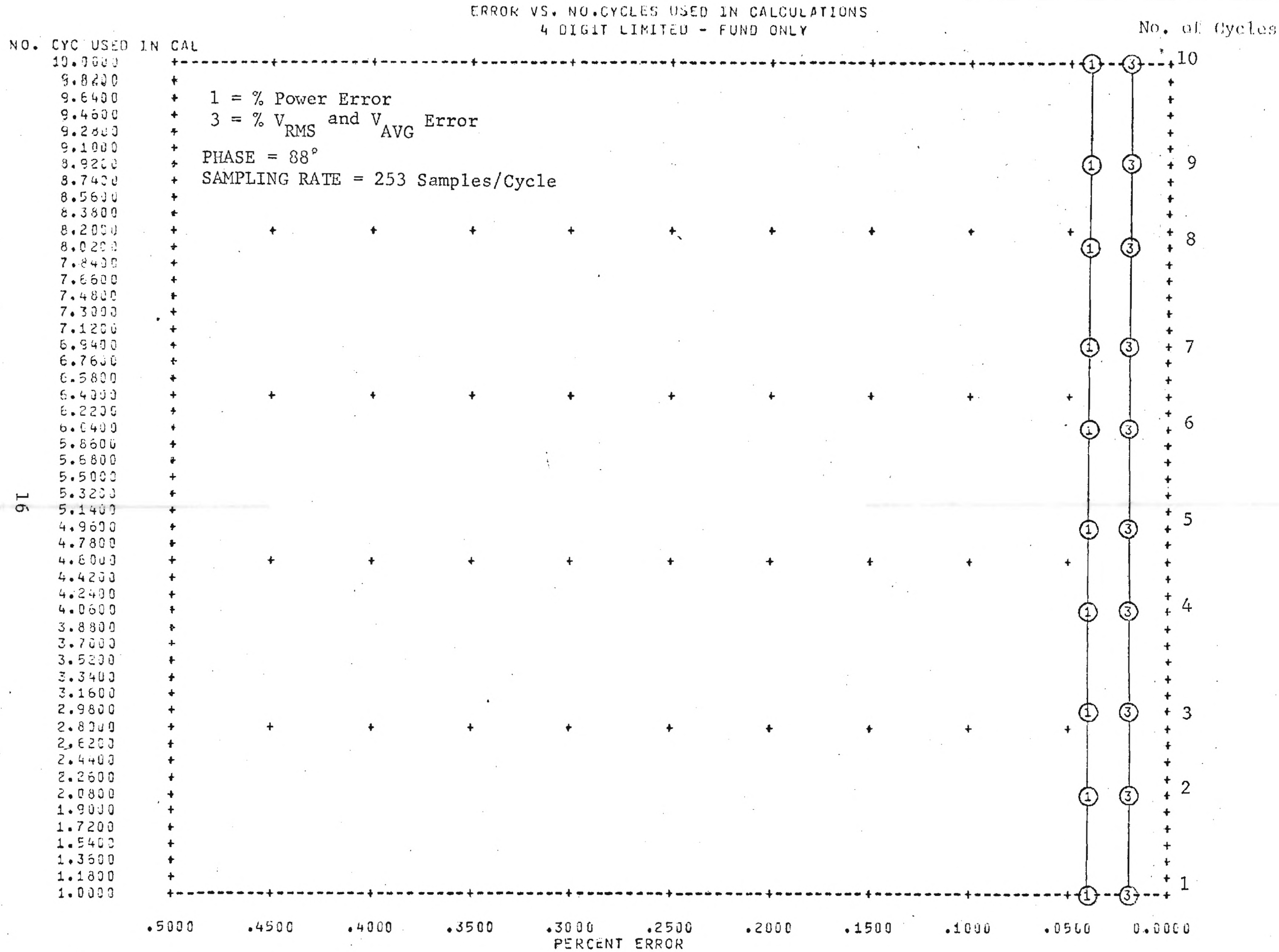

Fig 5b. Error vs. K2 (4-digit bit-limited, fundamental only).

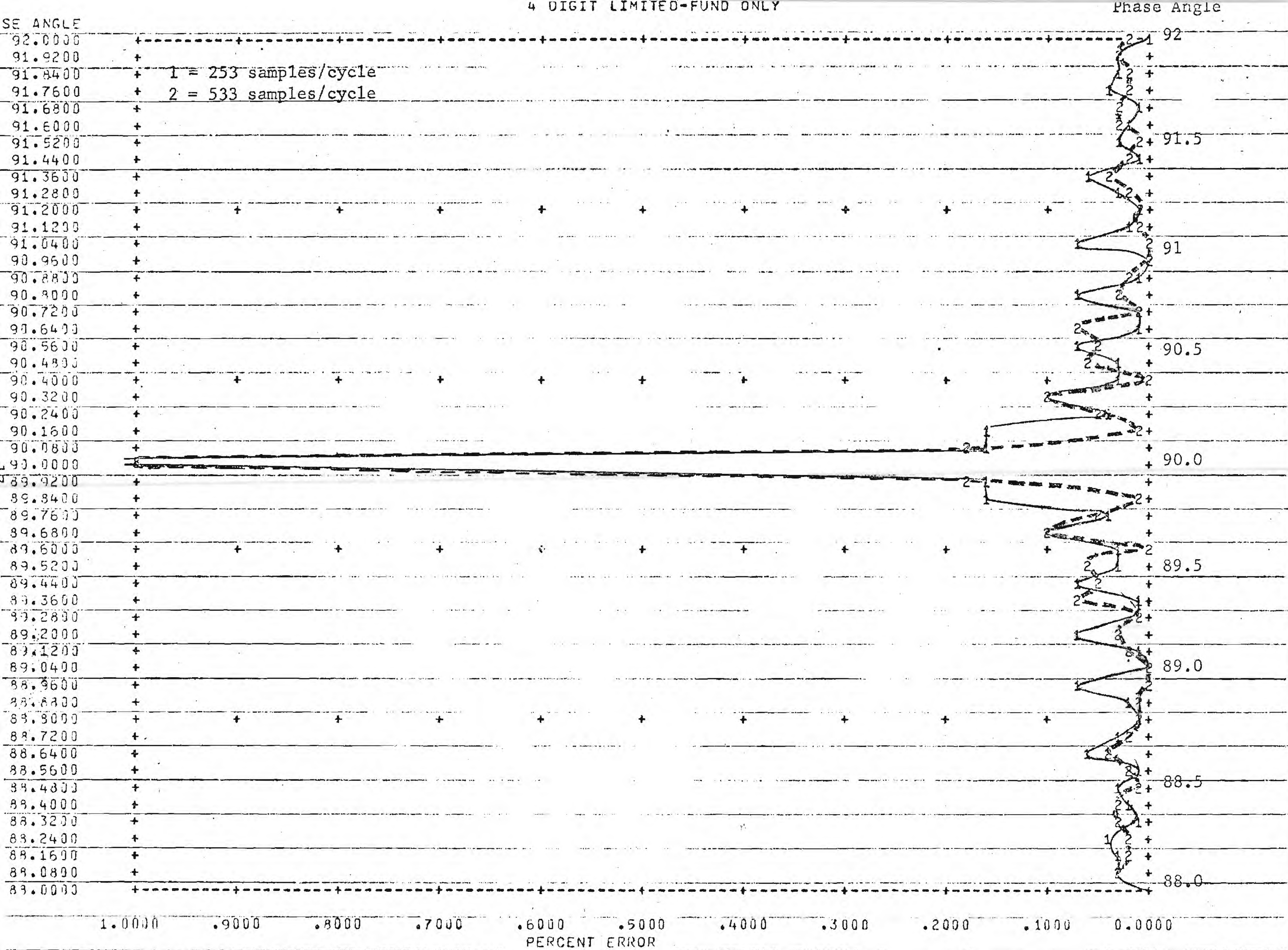

Fig 5c. Power Error vs. Phase (4-digit bit-limited, fundamental only)

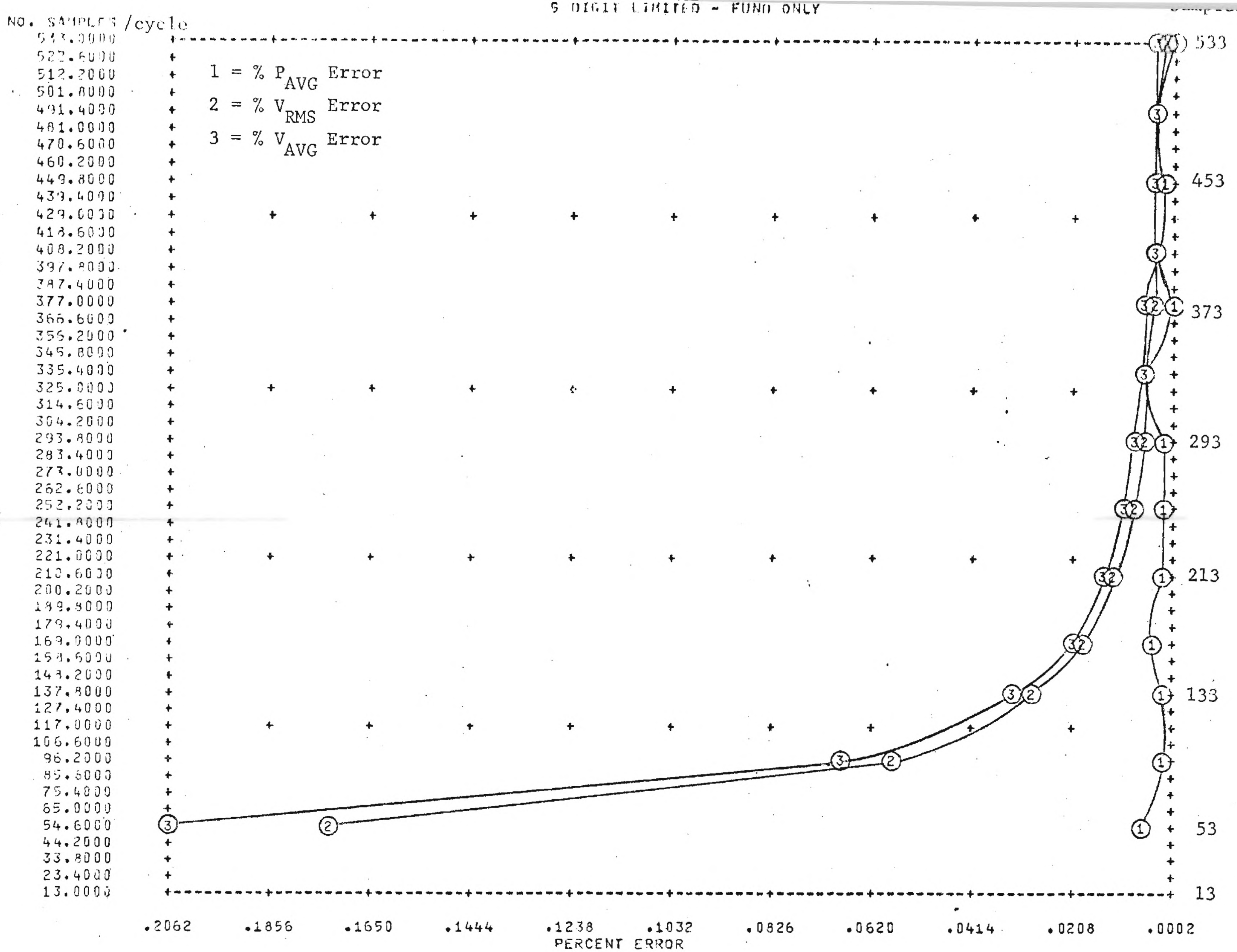

Fig 6. Error vs. Sample Rate (5-digit bit-limited, fundamental only).

phase angles within approximately $\pm 0.25^\circ$ of 90° show an appreciable increase of error. This increase is due to:

(1) Errors due to bit-limiting (secondary error)

(2) Errors due to the numerical method (primary error).

(More accurate resolution would have been helpful here, but this necessity was realized too late for further analysis.) Outside this region errors are random and have an average of approximately 10^{-2} percent. (Note: synchronization loss of 10 μsec in this region corresponds to a phase change of 0.216 degrees and can be considered negligible.)

Figure 6 curves imply that no appreciable decrease in error occurs for V_{AVG} and V_{RMS} when bit-limiting is increased to 5 digits but P_{AVG} decreases by a power of ten.

Since four-digit bit-limiting is the probable final choice, a method to obtain 3-phase power error from Figure 5c is outlined below (an example is given also).

Define:

single phase power $= EI \cos \theta = P$

calculated power $= P^*$

power error $= \dfrac{P^* - P}{P} = e$ (fractional error)

Since 3-phase power is:

$$P = EI \cos \theta_1 + EI \cos \theta_2 + EI \cos \theta_3 = P_1 + P_2 + P_3$$

then,

$$e = \frac{(P_1* + P_2* + P_3*) - (P_1 + P_2 + P_3)}{(P_1 + P_2 + P_3)}$$

$$= \frac{P_1e_1 + P_2e_2 + P_3e_3}{P} \quad ,$$

where

$$e_i = \frac{P_i* - P_i}{P_i} \quad ; \quad i = 1, 2, 3 \quad ,$$

or, by using the triangular inequality, an upper bound is:

$$|e| \leq \frac{|\cos \theta_1|\ e_1 + |\cos \theta_2|\ e_2 + |\cos \theta_3|\ e_3}{|\cos \theta_1| + |\cos \theta_2| + |\cos \theta_3|}$$

As an example, consider:

$P_1 = 15000$ W	with	$\theta_1 = 88.5°$	and	K1 = 253 samples/cycle
$P_2 = 10000$ W		$\theta_2 = 89°$		K2 = 2 cycles
$P_3 = 5000$ W		$\theta_3 = 89.5°$		

From Figure 5c, using θ_1, θ_2, θ_3 as above:

$e_1 = 0.03157\% \simeq 0.00032$

$e_2 = 0.0202\% \simeq 0.00020$

$e_3 = 0.0286\% \simeq 0.00029$

Therefore,

$$|e| \leq \frac{(0.02618)\ (3.2\text{x}10^{-4}) + (0.01745)\ (2\text{x}10^{-4}) + (0.00873)\ (2.9\text{x}10^{-4})}{(0.02618) + (0.01745) + (0.00873)}$$

and,

$$|e| \leq .0277\%$$

V. HARDWARE

A. Sample-and-Hold, S/H:

A sample-and-hold is used to quantize the input values of analog voltage and current, and considerations of input accuracy in terms of droop rate and aperture uncertainty time are design parameters.

A droop rate of 10mv/sec will suffice and represents a negligible input amplitude error.

An aperture uncertainty time of 10nsec corresponds to negligible phase (or sync) variations.

A sample-and-hold (the SHA-6) manufactured by Analog Devices at a per unit cost of $375 meets these specifications.

B. Analog-to-Digital Converter, A/D:

Conversion of the analog signal to a digital signal with tolerable error requires a 14-bit A/D. Thus, the digital signal is accurate to within ± 6 μv of the quantized analog signal.

Negligible loss of amplitude in the S/H requires an A/D conversion time of approximately 50 μsec.

A device (the ADC-149-14B) as specified above is produced by Datel at a per unit cost of $279.

C. Typical System:

A feasible system is shown in Figure 7. In addition to the hardware above, latches, multiplexer, clock, power supply, minicomputer, and miscellaneous wire, solder, etc. will be required. Exact specification of these devices is not critical.

An approximate system cost may be:

DEVICE	PER UNIT COST	NO. REQUIRED	TOTAL COST
S/H	$ 375	6	$ 2250
A/D	279	6	1674
Latch	15	6	90
Multiplexer	100	1	100
Clock	150	1	150
Power Supply	150	1	150
Miscellaneous	100		100
Sub-Total	$969		$4514
PDP 11	$17,440		$17,440
Total			$21,954

Note: An alternate system employing a dual A/D which samples two lines simultaneously, requiring three 14-bit lines into the PDP 11, would possibly be less expensive.

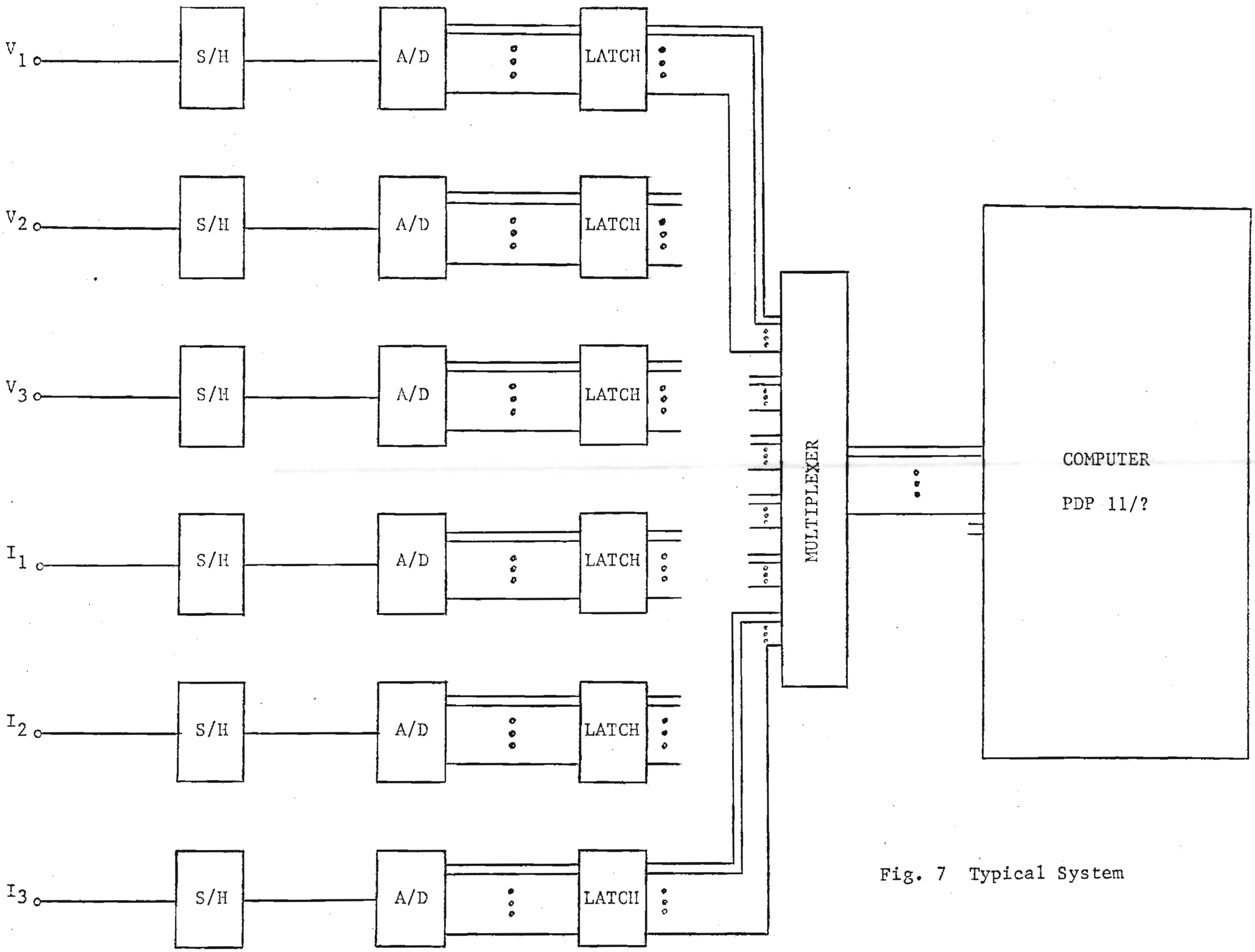

Fig. 7 Typical System

VI. CONCLUSIONS

The conclusions of this report are listed below:

A. RMS values can be calculated with an error less than 0.1% when the input data is accurate to a sign and 4 digits.

B. AVG values can be calculated with an error less than 0.1% when the input data is accurate to a sign and 4 digits.

C. Average power can be calculated with a numerical error on the order of 10^{-7}%. This error varies greatly around a phase angle of 90°. When input data is limited to an accuracy of a sign and 4 digits the error is around 10^{-1}%. These two errors can be superimposed to get the composite single phase error.

D. Three phase error calculations for P_{AVG} can be made using the single phase curves and the equation developed in Section III. In general, this indicates P_{AVG} can be calculated with an error less than 1%.

E. A sampling rate of 200 to 300 samples per cycle is sufficient to ensure the accuracy required. One cycle of data will give the best results. This requires an input of two cycles of raw data to cover starting and stopping conditions.

F. The sampling hardware will contribute negligible error when fast (10 nsec) sample and hold amplifiers are used with high accuracy (14 bit) analog to digital converters.

G. The hardware can be configured to sample two signals at a time and sequence through the three phases. This will save some hardware and decrease the input data rates. The signal switching will introduce some hardware shielding problems, however.

H. Data storage will require the number of signals (6) times the sample rate per cycle times the number of cycles (2). At a sample rate of 200 this implies 2400 words. At a sample rate of 300 the number is 3600 words. Total memory required is expected to be 8 K words.

APPENDIX

(Data for Figures 3 through 6)

SAMP	EPHR	EVRMS	EVAVG
.5300E+02	.9681E-08	.1657E+00	.2049E+00
.9300E+02	.5530E-08	.5521E-01	.6656E-01
.1330E+03	.3901E-08	.2727E-01	.3254E-01
.1730E+03	.3045E-08	.1620E-01	.1924E-01
.2130E+03	.2511E-08	.1072E-01	.1269E-01
.2530E+03	.2174E-08	.7618E-02	.8994E-02
.2930E+03	.1898E-08	.5689E-02	.6706E-02
.3330E+03	.1763E-08	.4410E-02	.5192E-02
.3730E+03	.1533E-08	.3518E-02	.4138E-02
.4130E+03	.1461E-08	.2872E-02	.3375E-02
.4530E+03	.1297E-08	.2389E-02	.2806E-02
.4930E+03	.1335E-08	.2018E-02	.2369E-02
.5330E+03	.1295E-08	.1727E-02	.2027E-02

Data for Fig. 3a.

.1623E+01	.2174E-08	.1295E-08
.8805E+02	.2276E-08	.1364E-08
.8810E+02	.2339E-08	.1366E-08
.8815E+02	.2341E-08	.1362E-08
.8820E+02	.2451E-08	.1439E-08
.8825E+02	.2532E-08	.1487E-08
.8830E+02	.2643E-08	.1567E-08
.8835E+02	.2636E-08	.1546E-08
.8840E+02	.2737E-08	.1598E-08
.8845E+02	.2865E-08	.1665E-08
.8850E+02	.2980E-08	.1736E-08
.8855E+02	.2983E-08	.1743E-08
.8860E+02	.3137E-08	.1843E-08
.8865E+02	.3275E-08	.1862E-08
.8870E+02	.3453E-08	.2041E-08
.8875E+02	.3508E-08	.2036E-08
.8880E+02	.3664E-08	.2123E-08
.8885E+02	.3881E-08	.2244E-08
.8890E+02	.4081E-08	.2354E-08
.8895E+02	.4127E-08	.2351E-08
.8900E+02	.4473E-08	.2575E-08
.8905E+02	.4632E-08	.2695E-08
.8910E+02	.5032E-08	.2849E-08
.8915E+02	.5140E-08	.2949E-08
.8920E+02	.5460E-08	.3100E-08
.8925E+02	.5959E-08	.3457E-08
.8930E+02	.6386E-08	.3694E-08
.8935E+02	.6659E-08	.3658E-08
.8940E+02	.7378E-08	.4158E-08
.8945E+02	.8029E-08	.4586E-08
.8950E+02	.9007E-08	.5164E-08
.8955E+02	.9710E-08	.5478E-08
.8960E+02	.1098E-07	.6083E-08
.8965E+02	.1264E-07	.7224E-08
.8970E+02	.1489E-07	.8450E-08
.8975E+02	.1748E-07	.9535E-08
.8980E+02	.2206E-07	.1233E-07
.8985E+02	.2943E-07	.1633E-07
.8990E+02	.4502E-07	.2533E-07
.8995E+02	.8789E-07	.4850E-07
.9000E+02	.1693E+01	.9205E+00
.9005E+02	.8911E-07	.4907E-07
.9010E+02	.4482E-07	.2515E-07
.9015E+02	.2913E-07	.1571E-07
.9020E+02	.2216E-07	.1208E-07
.9025E+02	.1768E-07	.9623E-08
.9030E+02	.1506E-07	.8218E-08
.9035E+02	.1252E-07	.6705E-08
.9040E+02	.1100E-07	.5957E-08
.9045E+02	.9925E-08	.5410E-08
.9050E+02	.8976E-08	.4785E-08
.9055E+02	.7971E-08	.4143E-08
.9060E+02	.7418E-08	.3948E-08
.9065E+02	.6868E-08	.3605E-08
.9070E+02	.6485E-08	.3452E-08
[illegible]	[illegible]	[illegible]
.9120E+02	.3704E-08	.1957E-08
.9125E+02	.3600E-08	.1882E-08
.9130E+02	.3495E-08	.1797E-08
.9135E+02	.3277E-08	.1663E-08
.9140E+02	.3222E-08	.1630E-08
.9145E+02	.3089E-08	.1583E-08
.9150E+02	.3051E-08	.1578E-08
.9155E+02	.2879E-08	.1466E-08
.9160E+02	.2789E-08	.1403E-08
.9165E+02	.2749E-08	.1415E-08
.9170E+02	.2685E-08	.1372E-08
.9175E+02	.2530E-08	.1256E-08
.9180E+02	.2510E-08	.1276E-08
.9185E+02	.2444E-08	.1239E-08
.9190E+02	.2413E-08	.1235E-08
.9195E+02	.2286E-08	.1135E-08
.9200E+02	.2245E-08	.1123E-08
.9205E+02	.2221E-08	.1127E-08
.9210E+02	.2183E-08	.1096E-08
.9215E+02	.2071E-08	.1037E-08
.9220E+02	.2073E-08	.1032E-08
.9225E+02	.2015E-08	.9979E-09
.9230E+02	.2011E-08	.1019E-08
.9235E+02	.1912E-08	.9325E-09
.9240E+02	.1879E-08	.9237E-09
.9245E+02	.1871E-08	.9408E-09
.9250E+02	.1832E-08	.9142E-09
.9255E+02	.1754E-08	.8579E-09
.9260E+02	.1744E-08	.8646E-09
.9265E+02	.1716E-08	.8545E-09
.9270E+02	.1709E-08	.8537E-09
.9275E+02	.1635E-08	.8033E-09
.9280E+02	.1613E-08	.7878E-09
.9285E+02	.1611E-08	.8003E-09
.9290E+02	.1581E-08	.7842E-09
.9295E+02	.1520E-08	.7301E-09

0 x

Phase Percent Error

Data for Fig. 3b.

DATA LIST

SAMP	EPHR	EVRMS	EVAVG
.5300E+02	.2164E-07	.2581E+00	.3532E+00
.9300E+02	.1249E-07	.8856E-01	.1149E+00
.1330E+03	.8860E-08	.4422E-01	.5820E-01
.1730E+03	.6846E-08	.2642E-01	.3322E-01
.2130E+03	.5736E-08	.1755E-01	.2192E-01
.2530E+03	.4995E-08	.1250E-01	.1553E-01
.2930E+03	.4151E-08	.9349E-02	.1158E-01
.3330E+03	.3841E-08	.7256E-02	.8967E-02
.3730E+03	.3340E-08	.5795E-02	.7147E-02
.4130E+03	.3295E-08	.4734E-02	.5830E-02
.4530E+03	.2854E-08	.3940E-02	.4846E-02
.4930E+03	.2928E-08	.3330E-02	.4091E-02
.5330E+03	.2589E-08	.2852E-02	.3500E-02

Data for Fig. 4a.

.1523E+01	.4905E-08	.2589E-08
.8805E+02	.5095E-08	.2705E-08
.8810E+02	.5213E-08	.2781E-08
.8815E+02	.5324E-08	.2793E-08
.8820E+02	.5468E-08	.2879E-08
.8825E+02	.5635E-08	.2991E-08
.8830E+02	.5860E-08	.3114E-08
.8835E+02	.5953E-08	.3158E-08
.8840E+02	.6162E-08	.3221E-08
.8845E+02	.6384E-08	.3395E-08
.8850E+02	.6628E-08	.3465E-08
.8855E+02	.6770E-08	.3505E-08
.8860E+02	.7084E-08	.3713E-08
.8865E+02	.7338E-08	.3852E-08
.8870E+02	.7552E-08	.4062E-08
.8875E+02	.7878E-08	.4126E-08
.8880E+02	.8214E-08	.4286E-08
.8885E+02	.8555E-08	.4547E-08
.8890E+02	.9027E-08	.4774E-08
.8895E+02	.9349E-08	.4891E-08
.8900E+02	.9300E-08	.5151E-08
.8905E+02	.1042E-07	.5430E-08
.8910E+02	.1114E-07	.5867E-08
.8915E+02	.1167E-07	.6057E-08
.8920E+02	.1237E-07	.6383E-08
.8925E+02	.1326E-07	.6874E-08
.8930E+02	.1423E-07	.7396E-08
.8935E+02	.1514E-07	.7888E-08
.8940E+02	.1654E-07	.8598E-08
.8945E+02	.1795E-07	.9352E-08
.8950E+02	.1999E-07	.1043E-07
.8955E+02	.2197E-07	.1132E-07
.8960E+02	.2469E-07	.1268E-07
.8965E+02	.2847E-07	.1482E-07
.8970E+02	.3324E-07	.1726E-07
.8975E+02	.3948E-07	.2013E-07
.8980E+02	.4959E-07	.2543E-07
.8985E+02	.6501E-07	.3378E-07
.8990E+02	.1001E-06	.5243E-07
.8995E+02	.1983E-06	.1012E-06
.9000E+02	.3819E+01	.1959E+01
.9005E+02	.1979E-06	.1030E-06
.9010E+02	.9909E-07	.5155E-07
.9015E+02	.6517E-07	.3347E-07
.9020E+02	.4949E-07	.2544E-07
.9025E+02	.3955E-07	.2037E-07
.9030E+02	.3313E-07	.1724E-07
.9035E+02	.2809E-07	.1432E-07
.9040E+02	.2445E-07	.1249E-07
.9045E+02	.2201E-07	.1139E-07
.9050E+02	.1977E-07	.1009E-07
.9055E+02	.1778E-07	.9093E-08
.9060E+02	.1539E-07	.8346E-08
.9065E+02	.1513E-07	.7653E-08
.9070E+02	.1416E-07	.7242E-08
.9075E+02	.1312E-07	.6524E-08
.9080E+02	.1228E-07	.6097E-08

Data for Fig. 4b.

.9120E+02	.8188E-08	.4035E-08
.9125E+02	.7944E-08	.3978E-08
.9130E+02	.7649E-08	.3803E-08
.9135E+02	.7264E-08	.3506E-08
.9140E+02	.7046E-08	.3491E-08
.9145E+02	.6813E-08	.3367E-08
.9150E+02	.6661E-08	.3329E-08
.9155E+02	.6378E-08	.3113E-08
.9160E+02	.6163E-08	.3023E-08
.9165E+02	.6013E-08	.2982E-08
.9170E+02	.5839E-08	.2883E-08
.9175E+02	.5615E-08	.2702E-08
.9180E+02	.5517E-08	.2703E-08
.9185E+02	.5360E-08	.2636E-08
.9190E+02	.5254E-08	.2591E-08
.9195E+02	.5062E-08	.2469E-08
.9200E+02	.4923E-08	.2387E-08
.9205E+02	.4863E-08	.2372E-08
.9210E+02	.4751E-08	.2320E-08
.9215E+02	.4589E-08	.2203E-08
.9220E+02	.4514E-08	.2161E-08
.9225E+02	.4406E-08	.2102E-08
.9230E+02	.4362E-08	.2112E-08
.9235E+02	.4221E-08	.2020E-08
.9240E+02	.4134E-08	.1971E-08
.9245E+02	.4064E-08	.1949E-08
.9250E+02	.3988E-08	.1912E-08
.9255E+02	.3867E-08	.1837E-08
.9260E+02	.3930E-08	.1838E-08
.9265E+02	.3754E-08	.1804E-08
.9270E+02	.3713E-08	.1790E-08
.9275E+02	.3598E-08	.1701E-08
.9280E+02	.3546E-08	.1666E-08
.9285E+02	.3507E-08	.1687E-08
.9290E+02	.3453E-08	.1652E-08
.9295E+02	.3350E-08	.1589E-08
	0	x
Phase	Percent Error	

Data for Fig. 4b. Contd.

DATA LIST

SAMP	EPWR	EVRMS	EVAVG
.5300E+02	.1281E-01	.1846E+00	.2183E+00
.9300E+02	.4190E-02	.6904E-01	.8249E-01
.1330E+03	.3233E-01	.4101E-01	.4775E-01
.1730E+03	.2389E-01	.2893E-01	.3488E-01
.2130E+03	.3811E-01	.2296E-01	.2788E-01
.2530E+03	.4996E-02	.2005E-01	.2409E-01
.2930E+03	.2529E-01	.1816E-01	.2219E-01
.3330E+03	.1428E-01	.1683E-01	.2028E-01
.3730E+03	.2545E-01	.1600E-01	.1919E-01
.4130E+03	.1873E-01	.1561E-01	.1824E-01
.4530E+03	.3069E-01	.1378E-01	.1718E-01
.4930E+03	.2102E-01	.1513E-01	.1853E-01
.5330E+03	.1853E-01	.1371E-01	.1702E-01

Data for Fig. 5a.

DATA LIST .

NO. CYC	EPWR	EVRMS	EVAVG
.1000E+01	.4074E-01	.1982E-01	.2133E-01
.2000E+01	.4074E-01	.1982E-01	.2133E-01
.3000E+01	.4074E-01	.1982E-01	.2133E-01
.4000E+01	.4074E-01	.1982E-01	.2133E-01
.5000E+01	.4074E-01	.1982E-01	.2133E-01
.6000E+01	.4074E-01	.1982E-01	.2133E-01
.7000E+01	.4074E-01	.1982E-01	.2133E-01
.8000E+01	.4074E-01	.1982E-01	.2133E-01
.9000E+01	.4074E-01	.1982E-01	.2133E-01
.1000E+02	.4074E-01	.1982E-01	.2133E-01

Data for Fig. 5b.

.8800E+01	.4996E-02	.1853E-01
.8805E+02	.2290E-01	.1593E-01
.8810E+02	.2807E-01	.2723E-01
.8815E+02	.2779E-01	.1975E-01
.8820E+02	.4602E-01	.3461E-01
.8825E+02	.3317E-01	.1849E-01
.8830E+02	.8239E-02	.2648E-01
.8835E+02	.2348E-01	.3405E-01
.8840E+02	.2346E-01	.2592E-01
.8845E+02	.7827E-03	.2309E-01
.8850E+02	.3157E-01	.1453E-01
.8855E+02	.1156E-01	.1997E-01
.8860E+02	.2198E-01	.1114E-01
.8865E+02	.5827E-01	.3782E-01
.8870E+02	.3148E-01	.2215E-01
.8875E+02	.5825E-01	.3026E-01
.8880E+02	.1231E-01	.8166E-02
.8885E+02	.4689E-01	.1172E-01
.8890E+02	.2292E-01	.1469E-01
.8895E+02	.7148E-01	.1041E-02
.8900E+02	.2024E-01	.4292E-01
.8905E+02	.5437E-03	.3536E-02
.8910E+02	.5565E-02	.1872E-01
.8915E+02	.4542E-01	.3654E-01
.8920E+02	.7138E-01	.3168E-01
.8925E+02	.5383E-02	.1283E-01
.8930E+02	.5467E-02	.1141E-01
.8935E+02	.6252E-02	.6864E-01
.8940E+02	.4726E-01	.4349E-02
.8945E+02	.7323E-01	.5269E-01
.8950E+02	.2863E-01	.5590E-01
.8955E+02	.1185E-01	.3289E-01
.8960E+02	.2941E-01	.2342E-02
.8965E+02	.8419E-01	.3447E-01
.8970E+02	.9683E-01	.1011E+00
.8975E+02	.3923E-01	.4772E-01
.8980E+02	.6289E-02	.1919E-01
.8985E+02	.1564E+00	.6195E-02
.8990E+02	.1594E+00	.1770E+00
.8995E+02	.6859E+00	.1874E+00
.9000E+02	.1001E+03	.1002E+03
.9005E+02	.6869E+00	.1874E+00
.9010E+02	.1594E+00	.1770E+00
.9015E+02	.1564E+00	.6192E-02
.9020E+02	.6286E-02	.1919E-01
.9025E+02	.3923E-01	.4772E-01
.9030E+02	.9683E-01	.1011E+00
.9035E+02	.8419E-01	.3447E-01
.9040E+02	.2942E-01	.2343E-02
.9045E+02	.1185E-01	.3288E-01
.9050E+02	.2863E-01	.5590E-01
.9055E+02	.7323E-01	.5269E-01
.9060E+02	.4726E-01	.4350E-02
.9065E+02	.6253E-02	.6864E-01
.9070E+02	.5466E-02	.1140E-01
.9075E+02	.5382E-02	.1283E-01
.9080E+02	.7138E-01	.3168E-01
.9085E+02	.4542E-01	.3654E-01

Data for Fig. 5c.

.9130E+02	.3148E-01	.2215E-01
.9135E+02	.5827E-01	.3782E-01
.9140E+02	.2198E-01	.1114E-01
.9145E+02	.1156E-01	.1997E-01
.9150E+02	.3157E-01	.1453E-01
.9155E+02	.7830E-03	.2309E-01
.9160E+02	.2346E-01	.2592E-01
.9165E+02	.2848E-01	.3405E-01
.9170E+02	.8239E-02	.2648E-01
.9175E+02	.3917E-01	.1849E-01
.9180E+02	.4602E-01	.3461E-01
.9185E+02	.2779E-01	.1975E-01
.9190E+02	.2807E-01	.2723E-01
.9195E+02	.2290E-01	.1593E-01
.9200E+02	.4996E-02	.1852E-01
.9205E+02	.4758E-01	.1992E-01
.9210E+02	.2764E-01	.2264E-01
.9215E+02	.1451E-01	.2030E-01
.9220E+02	.2352E-01	.4676E-01
.9225E+02	.3978E-01	.2383E-01
.9230E+02	.2184E-01	.1311E-01
.9235E+02	.2425E-01	.3474E-01
.9240E+02	.2416E-01	.2232E-01
.9245E+02	.3052E-01	.2358E-01
.9250E+02	.4811E-01	.2285E-01
.9255E+02	.1514E-01	.3527E-01
.9260E+02	.9908E-02	.2233E-01
.9265E+02	.3314E-01	.1510E-01
.9270E+02	.3654E-01	.2081E-01
.9275E+02	.4697E-01	.1063E-01
.9280E+02	.1887E-01	.3019E-01
.9285E+02	.2314E-01	.3127E-01
.9290E+02	.3426E-01	.2944E-01
.9295E+02	.4215E-01	.2747E-01
	Percent Error	
	253	533
Phase	(samples/cycle)	

Data for Fig. 5c. Contd.

DATA LIST

SAMP	EPWR	EVRMS	EVAVG
.5300E+02	.5512E-02	.1735E+00	.2062E+00
.9300E+02	.1938E-02	.5789E-01	.6823E-01
.1330E+03	.2634E-02	.2889E-01	.3400E-01
.1730E+03	.4007E-02	.1774E-01	.2088E-01
.2130E+03	.1597E-02	.1205E-01	.1421E-01
.2530E+03	.1417E-02	.8879E-02	.1046E-01
.2930E+03	.2373E-02	.6876E-02	.8124E-02
.3330E+03	.5343E-02	.5733E-02	.6795E-02
.3730E+03	.4161E-03	.4743E-02	.5607E-02
.4130E+03	.3389E-02	.4152E-02	.4916E-02
.4530E+03	.2010E-02	.3700E-02	.4437E-02
.4930E+03	.3834E-02	.3303E-02	.3896E-02
.5330E+03	.1754E-03	.2934E-02	.3530E-02

Data for Fig. 6.